Carbon in Comets: the Volatiles

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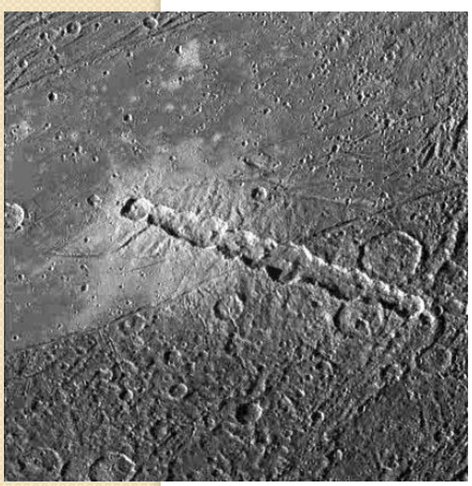
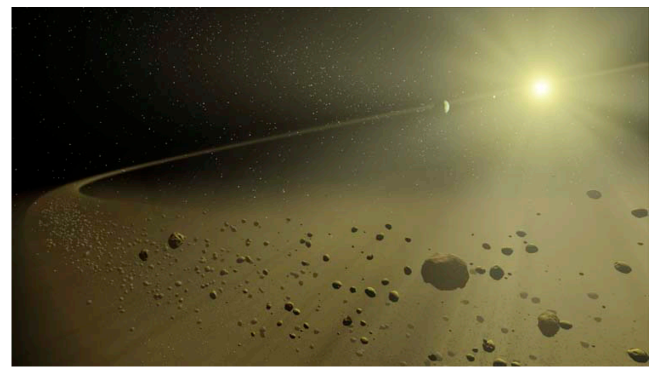
Comets play important roles in both **storage and delivery** of primordial material.



Comets brought important organics to the Earth. They continue to deposit material onto solar system bodies.

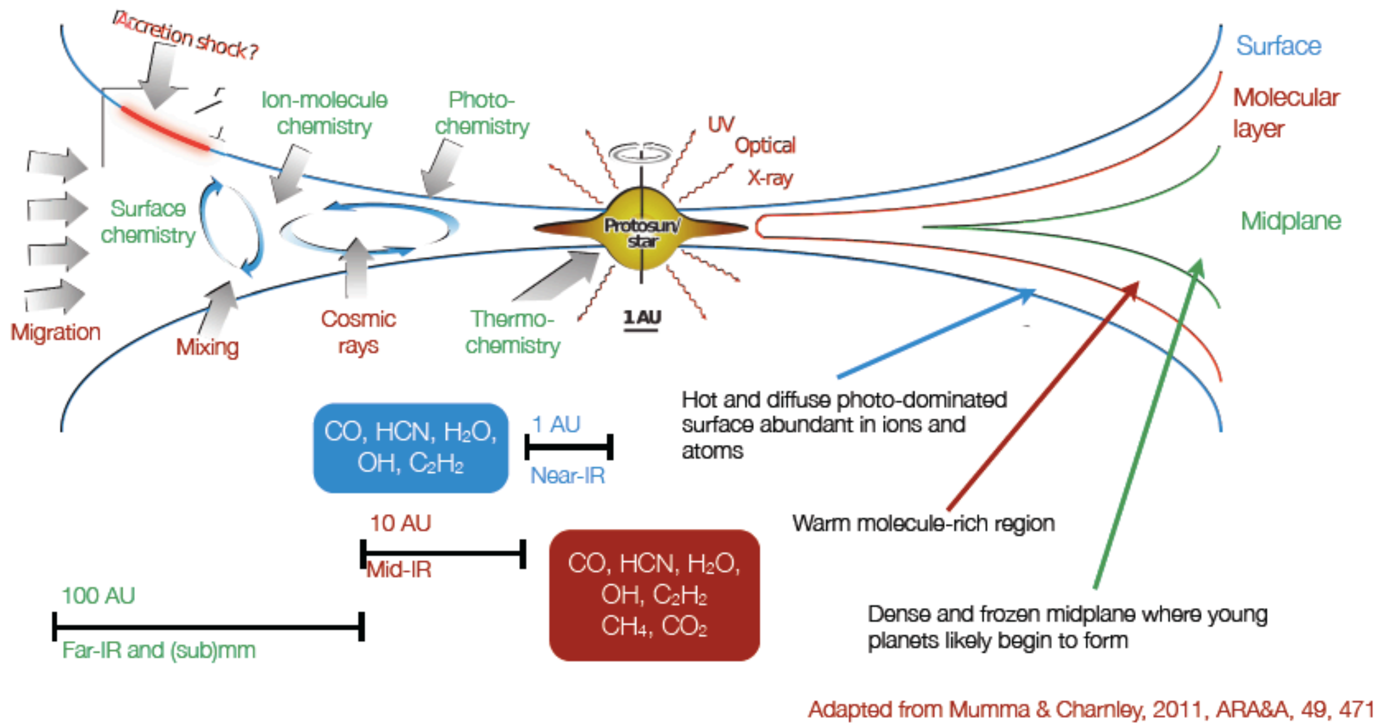
'Crater chain' on Ganymede showing serial craters from a disrupted object, likely a comet.
Galileo project, Brown University, JPL, NASA



Comets are well-preserved samples of ice, gas, dust and rock from the solar nebula.
NASA illustration.

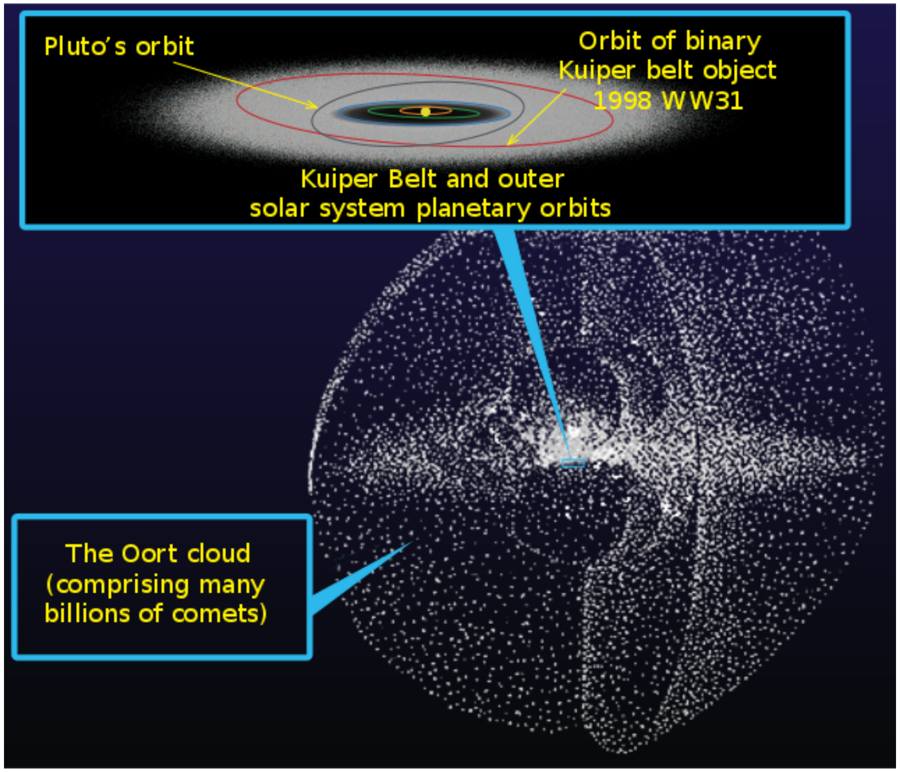
Physical and chemical processes in protostellar disks determine molecular abundances in comets

Lewis and Prinn, 1980, Prinn and Fegley 1989, A'Hearn et al. 2012, Walsh, C. et al. 2012, Li et al. 2014.



Comets formed in disk and then scattered

Comets formed from material leftover from planet formation and may contain preserved interstellar grains.



Levison1996, Walsh, K. et al. 2011, Dones et al. 2015

Orbital characteristics and chemical abundances are both important for testing formation models.

Long-period/Oort Cloud (P>200 yr)

Short-period (P<200 yr)
  Jupiter Family Comets
  Halley-Type

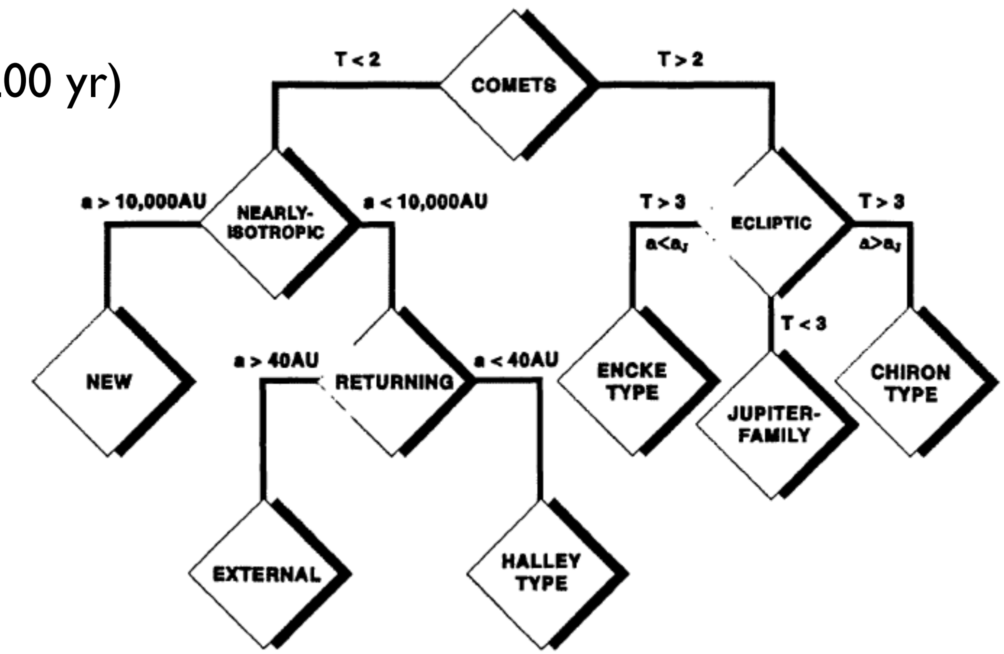
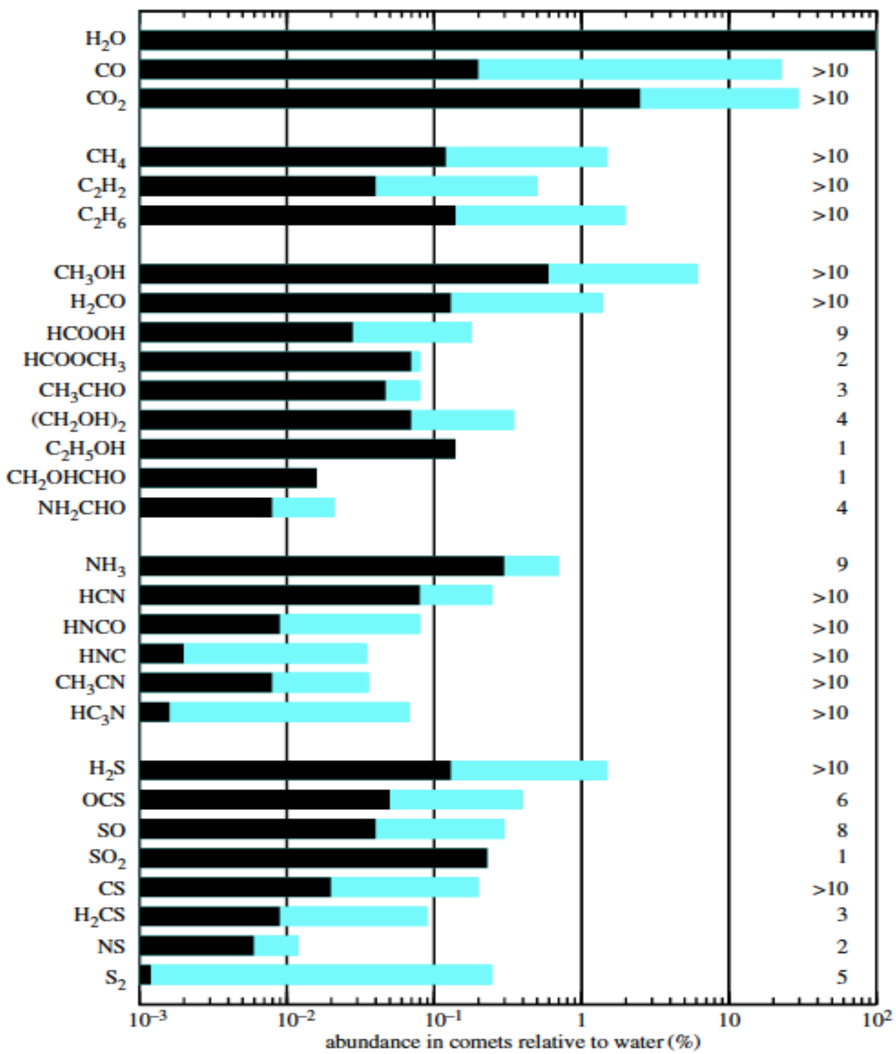


Figure 7. Proposed family tree for comets.

Levison 1996



Top carbon-bearing molecules in comets

Graph from Bockelee-Morvan and Biver 2017, See also DiSanti talk, Dello Russo et al. 2016.

CO, CO_2, CH_4, CH_3OH, C_2H_2, C_2H_6, and H_2CO are among the most abundant.

Cometary abundance ratios are not absolute: they can, and often do, change as a comet approaches and recedes from the Sun.

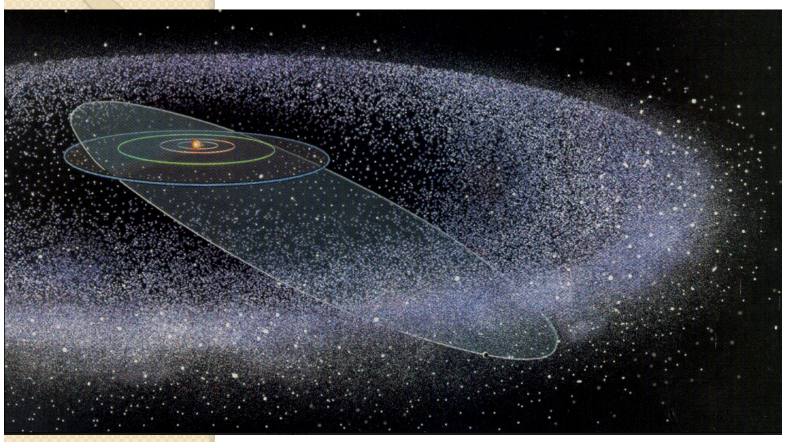
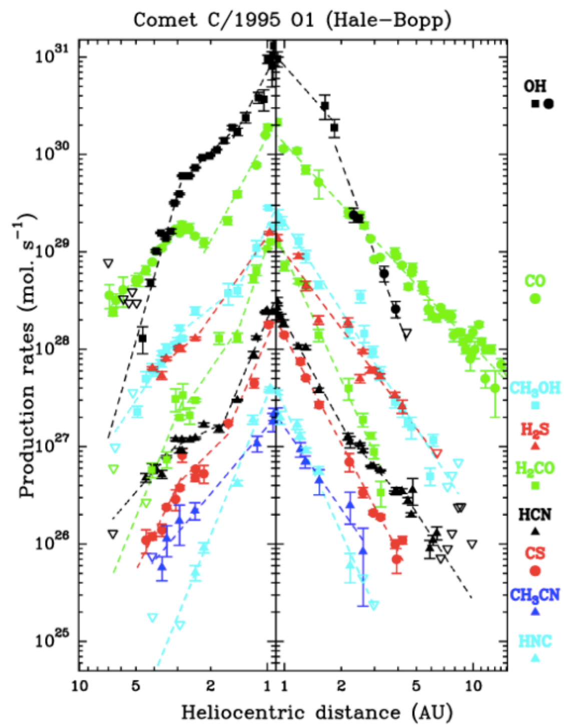


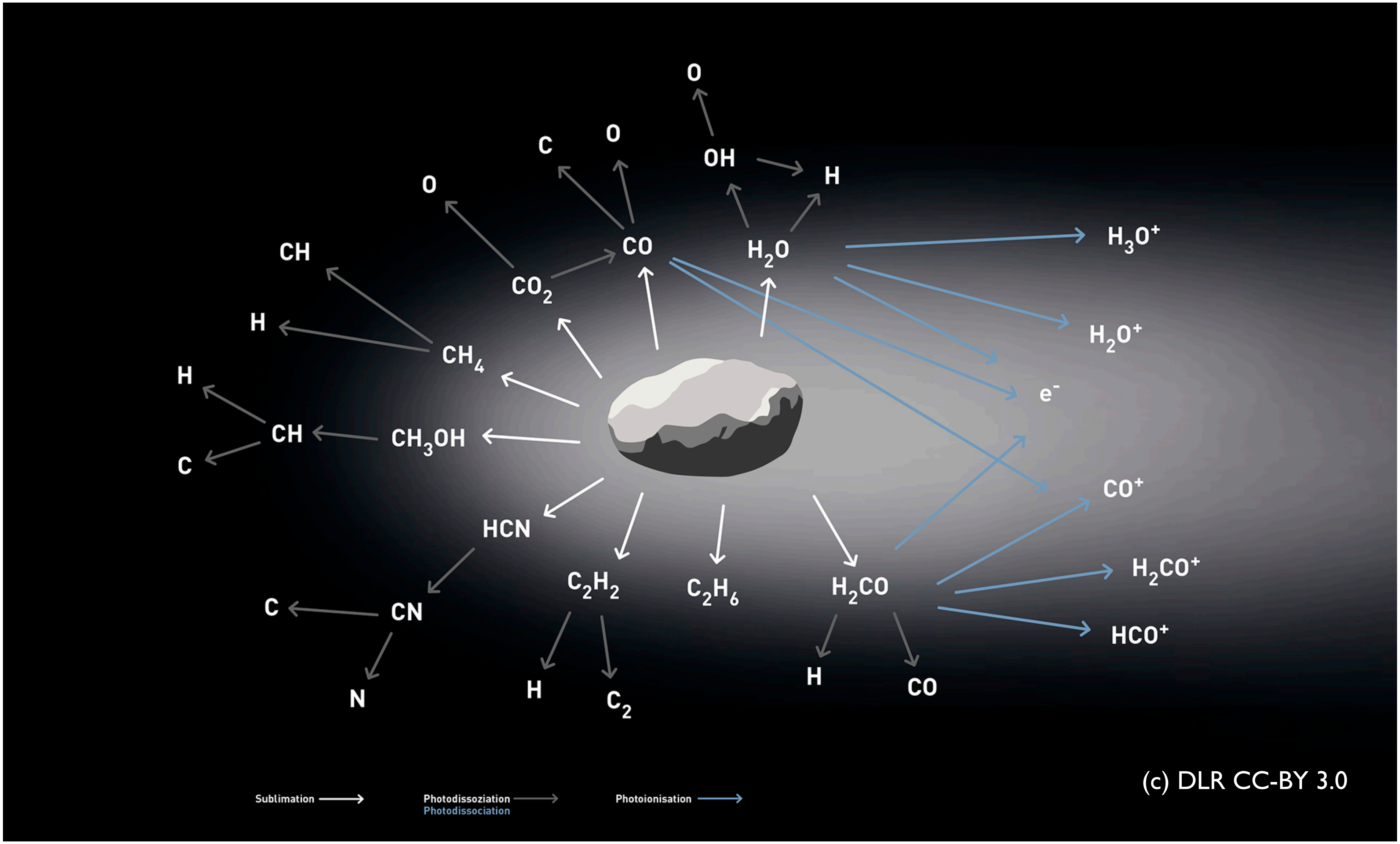
Image credit: James Schombert, U. Oregon

It is important to collect data for many values of heliocentric distance in order to correctly model the nucleus composition.

Also, some molecules are **“daughter products,”** formed via reactions of **“parent molecules”** with photons, and/or collisions with other particles.

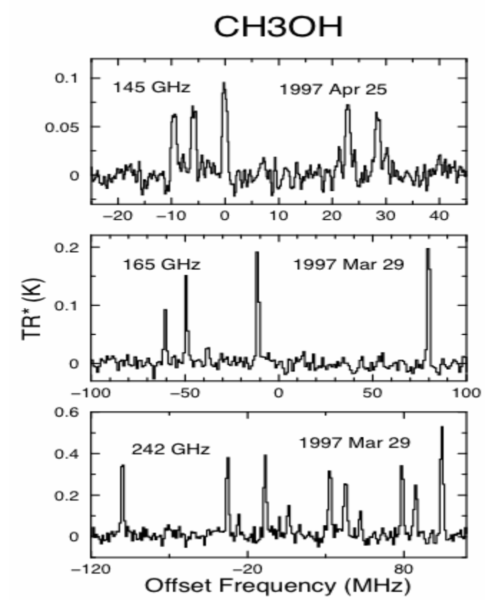


Biver et al. 1999


O
C
O
OH
H
O
CH
CO
H_2O
H_3O^+
CO_2
H
CH_4
H_2O^+
H
e^-
CH
CH_3OH
C
CO^+
HCN
H_2CO^+
C
CN
C_2H_2
C_2H_6
H_2CO
HCO^+
N
H
C_2
H
CO
(c) DLR CC-BY 3.0
Sublimation
Photodissoziation
Photodissociation
Photoionisation

Mm-spectra useful to determining how molecules emitted (and how much)

Arizona Radio Observatory
12-m telescope at Kitt Peak



Integrated line flux area
→ column density.

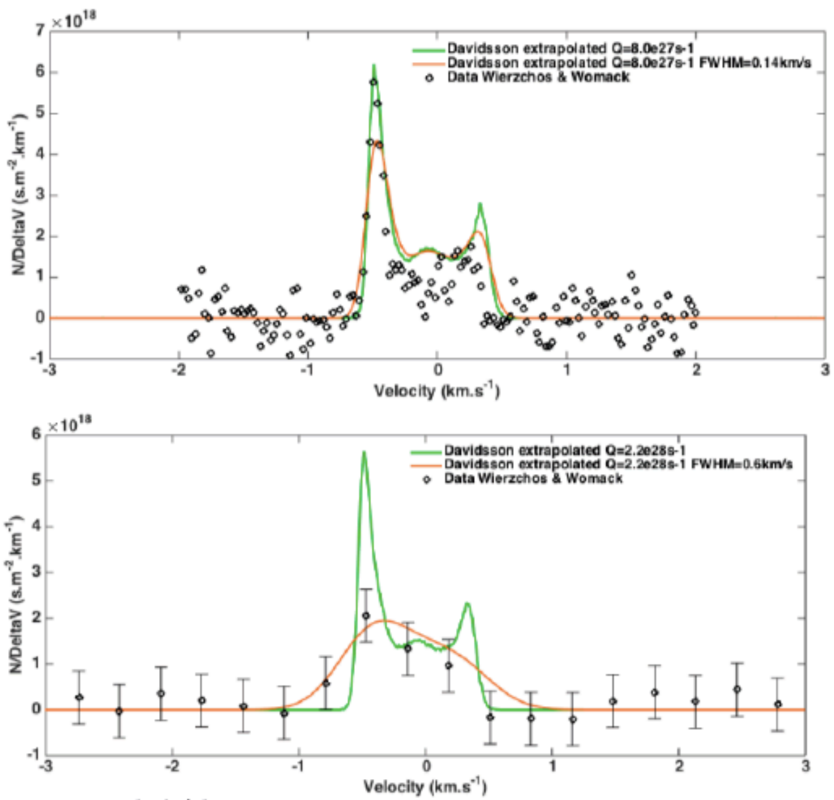


Figure 2: *Model/data comparison. CO J=2-1 spectra of 29P at two different resolutions (top obtained with IRAM 30-m telescope from Crovisier et al. 1995; bottom obtained with ARO SMT 10-m dish from Wierzchos and Womack, in prep.). This model is based on the surface distribution of gas flux and temperature given by the thermophysical models of Davidsson & Gutierrez and is convolved with other data the group has for 29P. Modeling is provided by collaborators Combi and Fougere.*

Millimeter-wavelength spectra has very high spectral resolution.

~ 0.05-0.3 km/s velocity resolution typical.

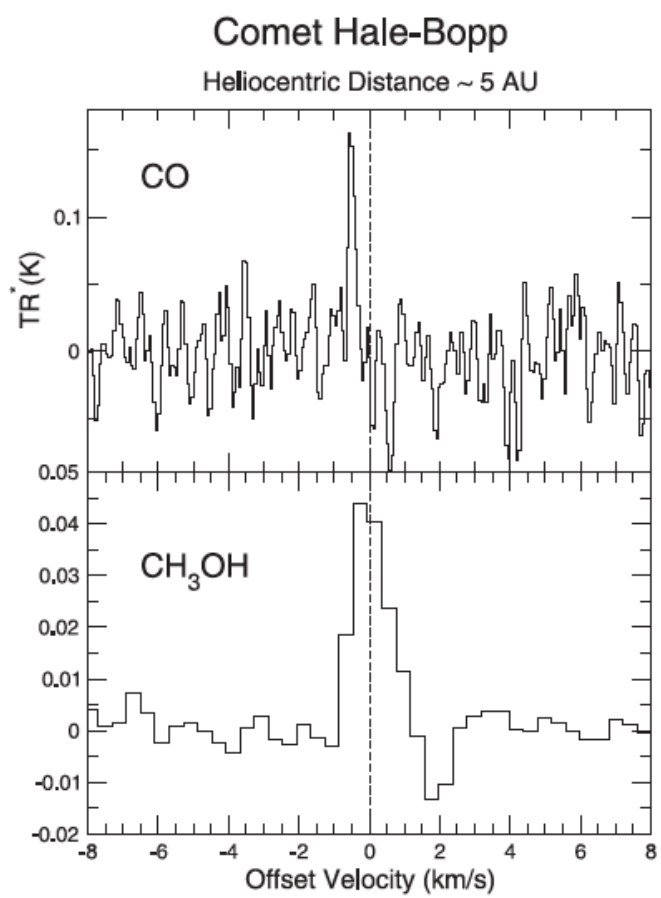
(Womack et al. in prep)

The CO emission line profile is <u>narrow</u> and <u>Doppler shifted</u>.

⇒Sunward side emission

Methanol's line is much <u>wider than CO and with no measurable Doppler shift</u>.

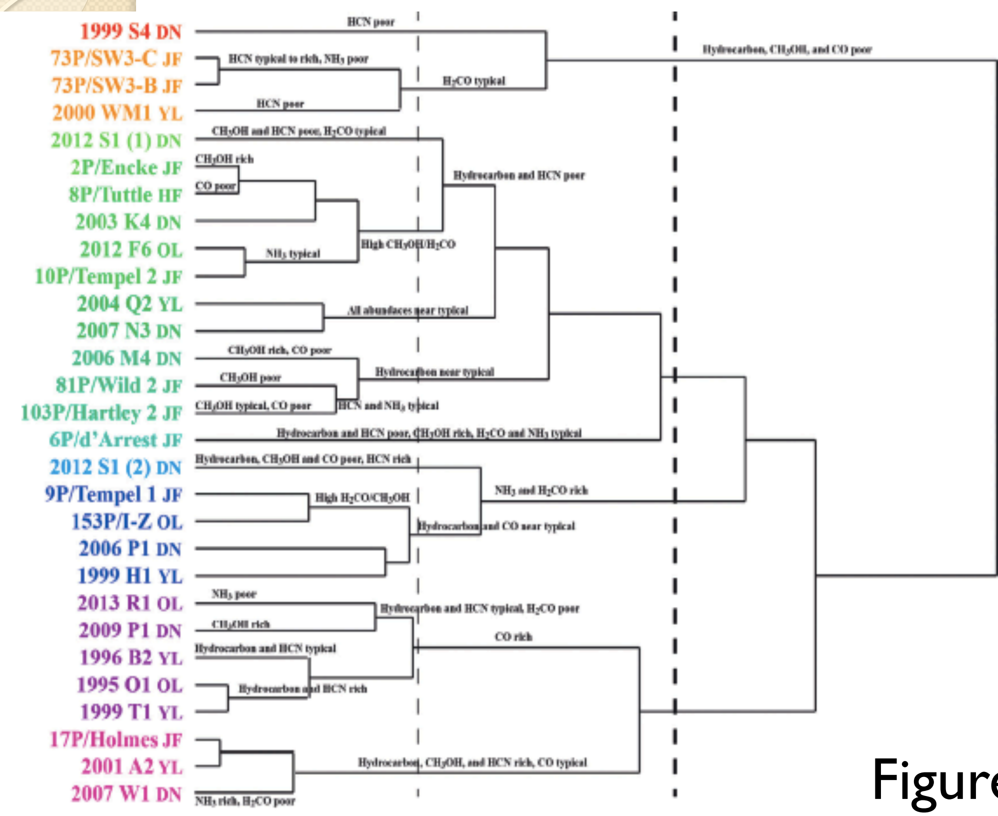
⇒Emission from a heated icy grain shell for CH_3OH



(Womack et al. 2017)

What do the abundances of carbon-species tell us about comets?

It's complicated!



GROUP A: Hydrocarbon, CH_3OH, and CO poor

Subgroup 1: Hydrocarbon, CH_3OH, HCN and CO poor

Subgroup 2: Hydrocarbon, CH_3OH, and CO poor, H_2CO and HCN typical

GROUP B: Hydrocarbon, HCN, H_2CO, and CO poor to typical, NH_3 typical

Subgroup 3: Hydrocarbon, CH_3OH, and HCN poor, H_2CO typical

Subgroup 4: Hydrocarbon, HCN and H_2CO poor, CH_3OH typical

Subgroup 5: Hydrocarbon, CH_3OH, HCN, NH_3, H_2CO, and CO near typical

Subgroup 6: Hydrocarbon, HCN, NH_3, and H_2CO typical, CO poor

Subgroup 7: Hydrocarbon and HCN poor, CH_3OH rich, NH_3 and H_2CO typical

GROUP C: NH_3 and H_2CO rich, Hydrocarbon and CO poor to typical, CH_3OH and HCN typical

Subgroup 8: Hydrocarbon, CH_3OH, and CO poor, HCN, NH_3, and H_2CO rich

Subgroup 9: Hydrocarbon and CO typical, NH_3 and H_2CO rich

Figure from Dello Russo et al. 2016.

Do carbon-species abundances "agree" with comet orbital classifications?

- Carbon-chain molecules (C_2 and C_3) appear depleted in Jupiter Family comets (A'Hearn et al. 1995).
- CO, CH_4, C_2H_2, C_2H_6 may also be depleted in JFCs (Dello Russo et al. 2016), but need more data.
- CO/CO_2 abundance ratios suggest that JFCs and long-period comets formed in overlapping regions between CO and CO_2 snow-lines, and CO_2 may be formed from CO on grain surfaces (A'Hearn et al. 2012).

Distant comets (>3 au) are a useful niche

- Water-ice sublimation is not strong beyond 3 au
- We can measure CO and CO_2 production without the blast of water-ice sublimation near the Sun.
- Sometimes, we can even study comets too far for CO_2 to sublimate (CO likely dominant), such as C/2017 K2 (Meech et al. 2017, Jewitt et al. 2017).
- Distant comets provide opportunities to test models of chemical reactions between CO and CO_2 on grains and in comae.

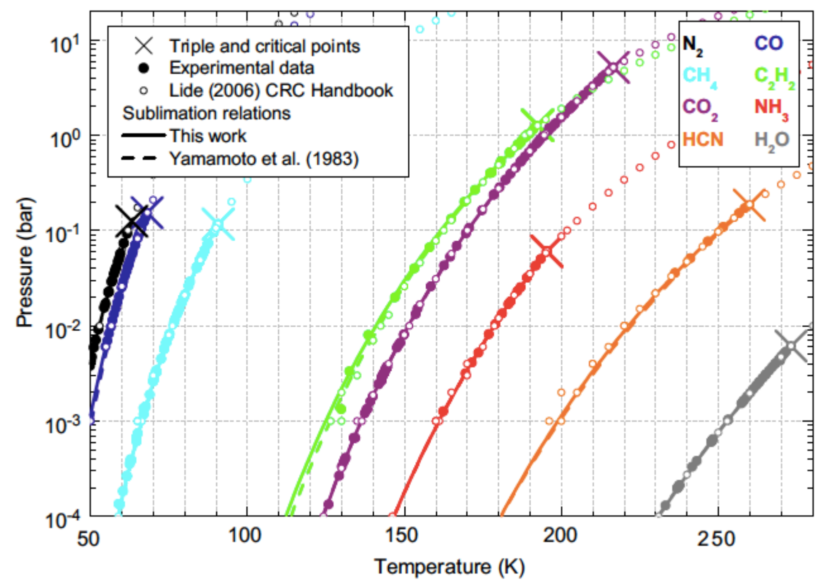
CO_2 and CO high abundances and low sublimation temperatures

Table 1
Sublimation Temperatures of Cometary Species

Species	Temperature[a] (K)
N_2	22
CO	25
CH_4	31
H_2S	57
C_2H_2	57
H_2CO	64
CO_2	72
HC_3N	74
NH_3	78
CS_2	78
SO_2	83
CH_3CN	91
HCN	95
CH_3OH	99
H_2O	152

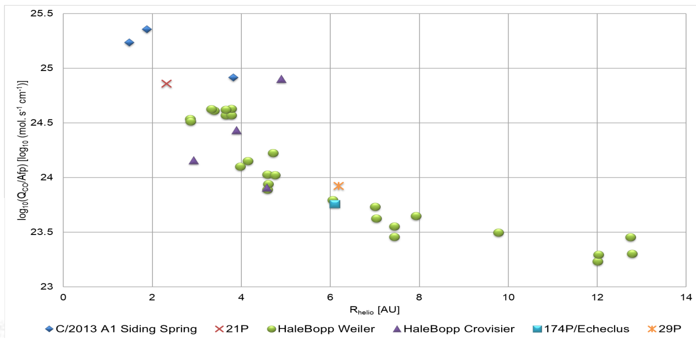
Note.
[a] Yamamoto 1985; Sekanina 1996.

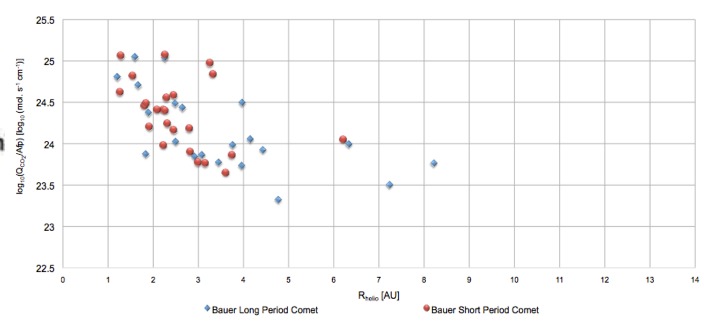
Womack et al. 2017



Fray et al. 2015

CO_2 and CO and gas/dust ratios in comets may show different heliocentric dependence





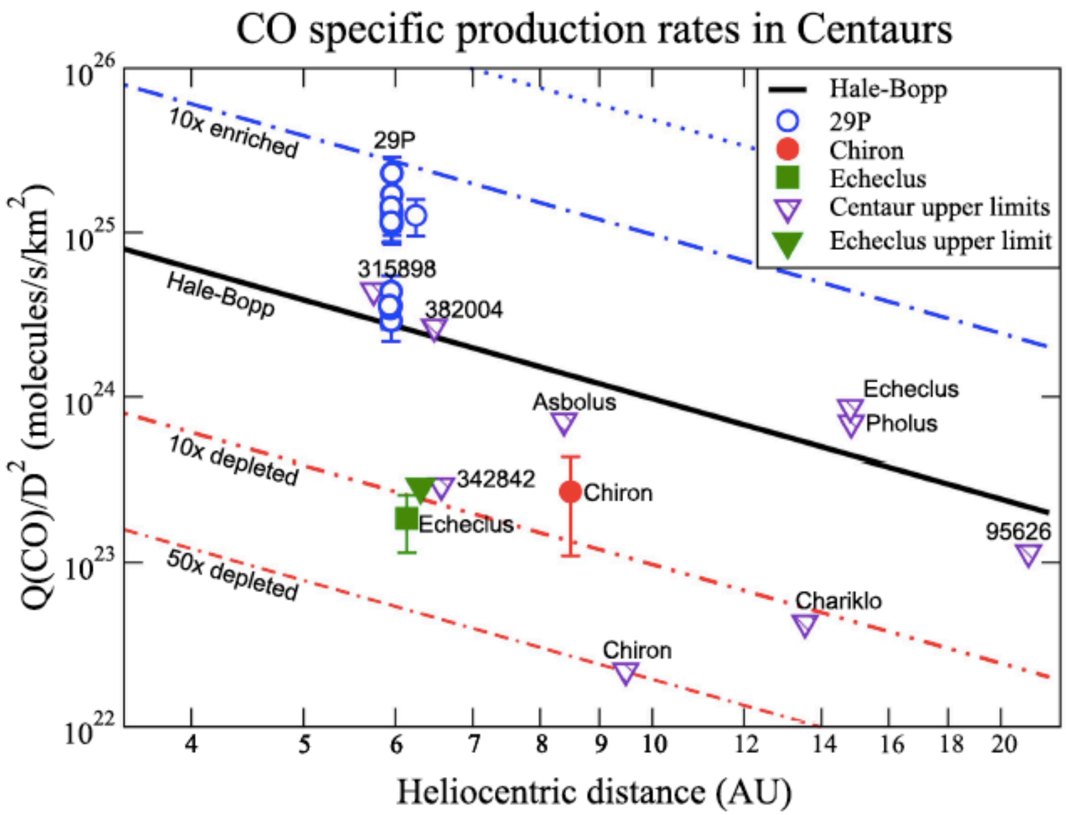
CO: break at 8 au?

CO2: break at 4 au?

Bauer et al. 2015,
Reach et al. 2013,
Ootsubo et al. 2012,
O. Harrington Pinto et al. 2017.

*Need more data!

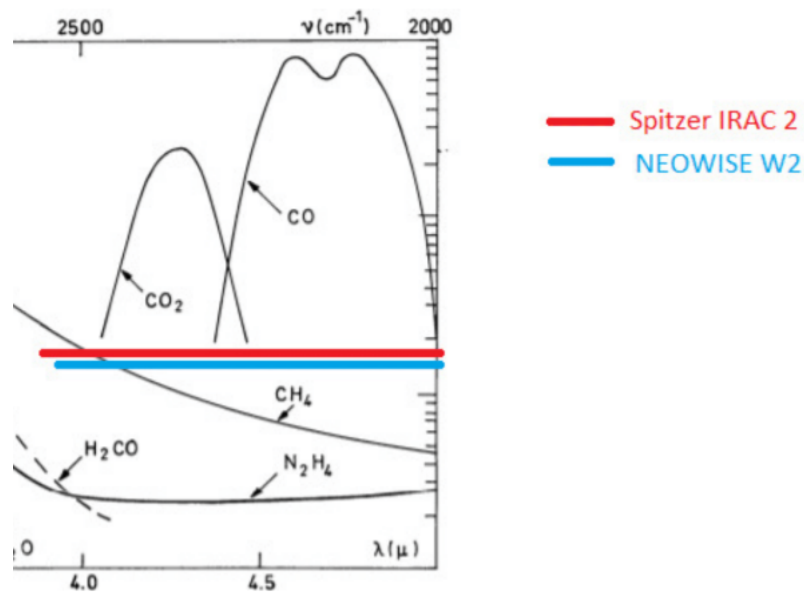
CO "specific" production rates may show CO-depletion for large Centaurs (Wierzchos et al. 2017)



Specific production rate = Q/D^2, where we assume production rate, Q, scales with comet nucleus diameter, D.

Important next steps for cometary CO and CO_2

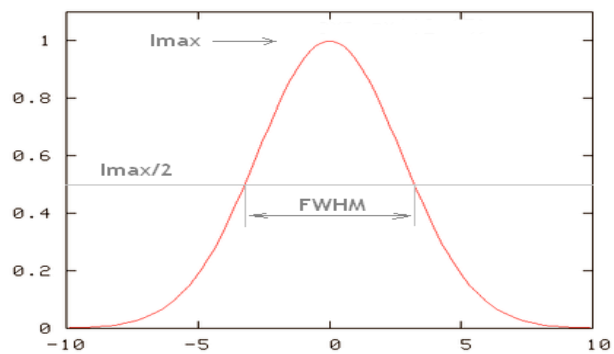
- More CO obs, especially over various *r* and beyond 5 au
- Simultaneous CO_2, CO obs (McKay talk)
- Revisit analysis of $CO+CO_2$ emission in IR bandpasses (O. Harrington Pinto, in prep.)
- Revisit $CO \rightarrow CO_2$ chemistry
- *ALMA and JWST*



Backup slides

We use spectra to measure gas outflow

- Symmetric outflow: estimate gas outflow velocity from HWHM of spectral lines



- Asymmetric (Sunward Side) ejection: Use Blue Wing of spectral lines

- CO_2 can be formed when OH and CO radicals combine. The temperature to make CO_2 depends on reaction rates and the deposition of water.
- CO gas is expected to be found at > 30 K in protoplanetary disks and can be trapped in comet at up to 70 K.
- The CO_2 and CO abundance ratios vary dramatically between comets of different dynamical families. (Ex: JFCs are not necessarily CO_2 abundant.)

We use spectra to constrain molecular excitation and production

$$T_B = \tau \frac{h\nu}{k} \{ [exp(\frac{h\nu}{kT_{ex}}) - 1]^{-1} - [exp(\frac{h\nu}{kT_{bg}}) - 1]^{-1} \},$$

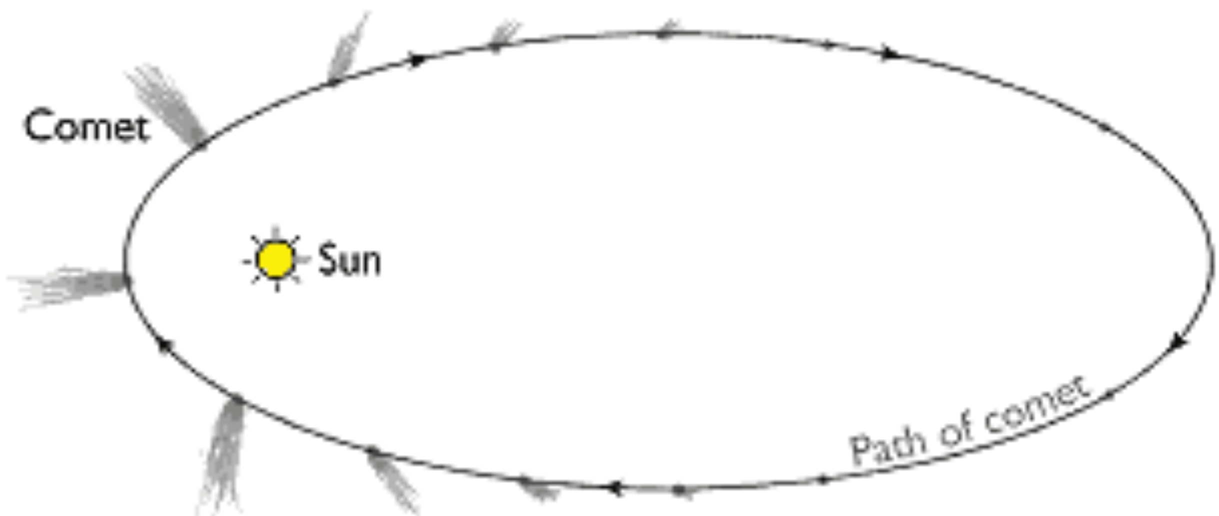
$$\tau = \frac{c^2}{8\pi\nu^2} \frac{2J+3}{2J+1} A_{ul} \frac{N_L}{\Delta\nu} [1 - exp \frac{-h\nu}{kT_{ex}}].$$

$$N_{tot} = \frac{N_L \zeta_{rot}}{2J+1} exp(\frac{\Delta E}{T_{rot}}),$$

$$n(r) = \frac{Q}{4\pi r^2 v_{exp}}.$$

Comet formation region around the CO and CO_2 snow lines (A'Hearn et al. 2012).

- Sublimation of H_2O, CO_2 and CO are the main drivers of activity



In progress: CO/HCN abundance ratios

(Wierzchos & Womack, 2018, submitted)

Table 2: Compiled Q(CO)/Q(HCN) ratios in CO-rich and other comets

Comet	Q(CO)/Q(HCN)	r^* (au)	Reference
C/2016 R2 (Pan-STARRS)	>**3500**	2.9	This paper
29P/Schwassmann-Wachmann 1	3300†	5.8	[1,20]
C/2006 W3 (Christensen)	243	3.2	[21]
C/1995 O1 (Hale-Bopp)	125-650	3	[3]
	52-91	0.9	[2,3,7]
C/2010 G2 (Hill)	70	2.5	[16]
C/1996 B2 (Hyakutake)	96	0.6, 0.7	[8]
C/1999 T1 (McNaught-Hartley)	46	1.3	[9,11]
C/2001 Q4 (NEAT)	31	1.0	[14]
C/2009 P1 (Garrad)	36	1.6, 2.1	[12,13,15,18]
C/2013 R1 (Lovejoy)	34	1.3	[17]
Oort Cloud Comets	28	-	[19]
Jupiter Family Comets	9	-	[19]
All comets	25	-	[19]

References: [1] Cochran & Cochran (1991), [2] Magee-Sauer et al. (1999), [3] Biver et al. (2002), [4] Disanti et al. (2002), [5] Dello Russo et al. (2002, 2004), [6] Magee-Sauer et al. (2002), [7] Brooke et al. (2003), [8] DiSanti et al. (2003), [9] Gibb et al.

Bulk C/N ratios vary significantly due to chemical reaction variations in formation zones

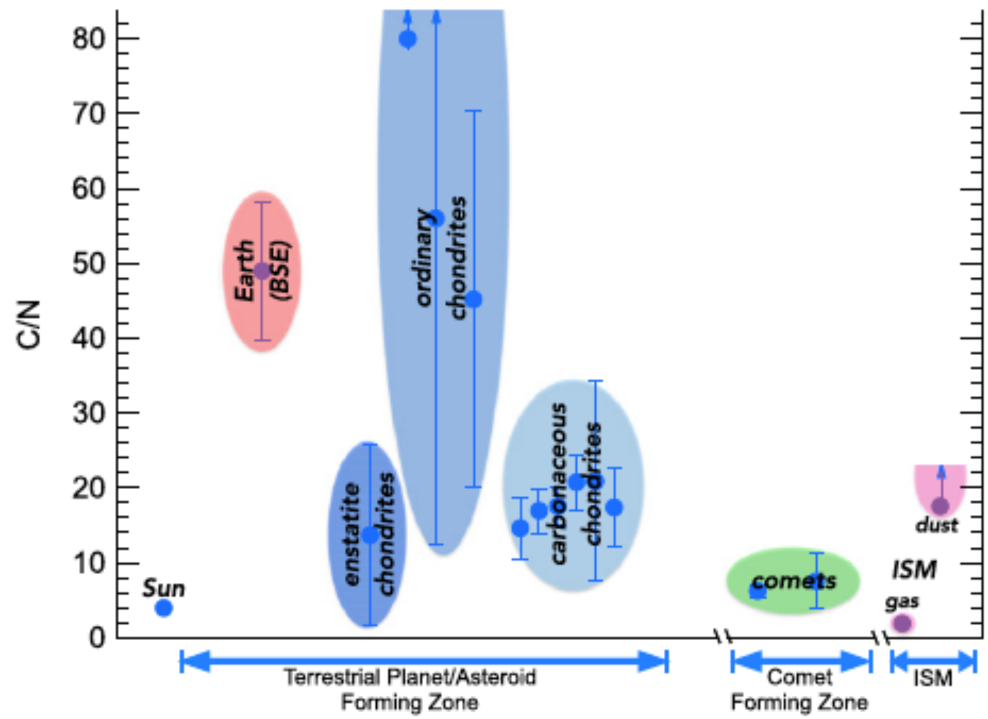
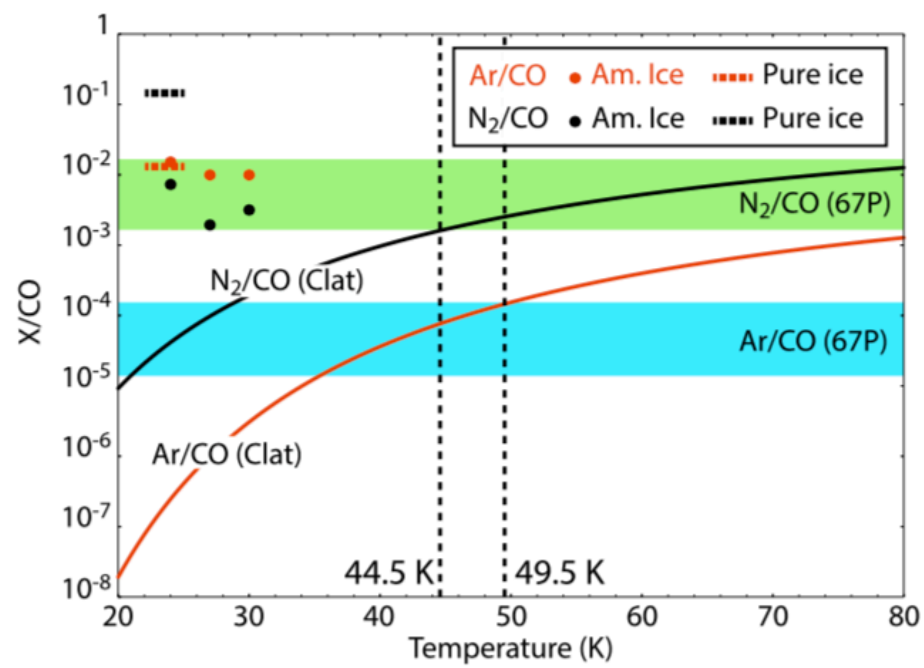


Figure 1 from Bergin et al. 2015

N2/CO abundance ratio depends on formation temperatures of the comet

THE ASTROPHYSICAL JOURNAL LETTERS, 819:L33 (5pp), 2016 March 10



Mousis et al. 2016